KamLAND, KamLAND-Zen and Beyond

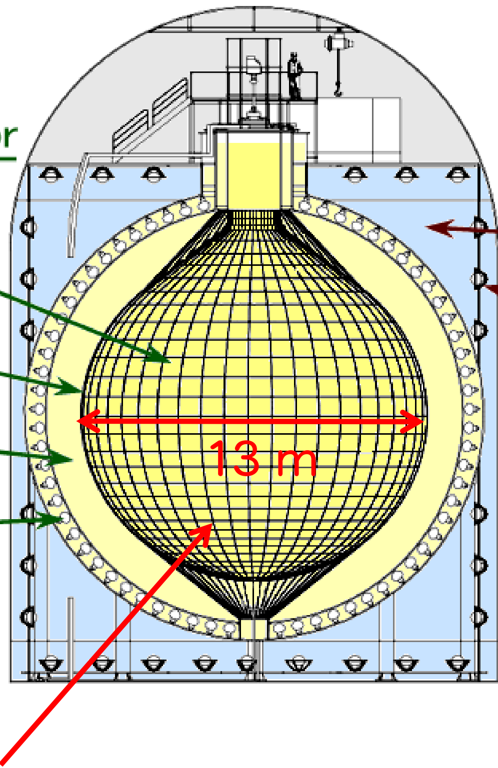
1. Double Beta Decay with KamLAND-Zen
   results, prospects and dreams

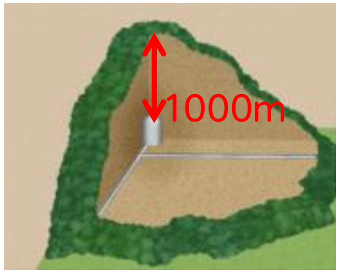
2. Evolution of KamLAND Scintillation Detector
   past 15 years and next 20 years

Sanshiro Enomoto
University of Washington

The Art of Experiment, LBL, 3 May 2014

KamLAND Detector: Shielded Calorimeter





Layered Shields

1000 m underground for muon reduction
Outer detector for active veto
Outer detector for neutron shield
Buffer oil for neutron/gamma shield
Balloon with EVOH for Radon shield
Acrylic wall for Radon shield
Air tightness for Radon/Kr shield

Active Volume

Large: 1000 ton, 13-m diameter
Clean: U: 3.5×10^{-18} g/g, Th: 5.2×10^{-17} g/g
Scintillator: 8000 photons/MeV
Viewed by PMTs: 1325 × 17-inch + 554 × 20-inch

Originally constructed to detect antineutrinos from surrounding reactors

"Evidence for Reactor Antineutrino Disappearance", PRL 90 021802 (2003)

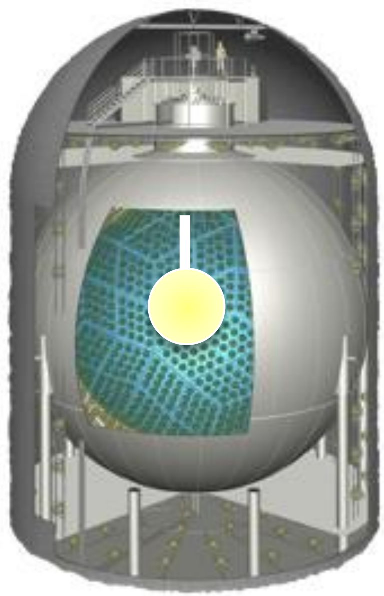
KamLAND as Active Low-BG Playground

Double Beta Decay

$CdWO_4$ Crystal
- small crystal tested with KamLAND

CaF_2 Crystal
- joint with CANDLES

Xe Dissolved Scintillator
- KamLAND-Zen ...



Sterile Neutrinos

Ce Source (CeLAND)
- 75 kCi ^{144}Ce
- place center or outer vessel

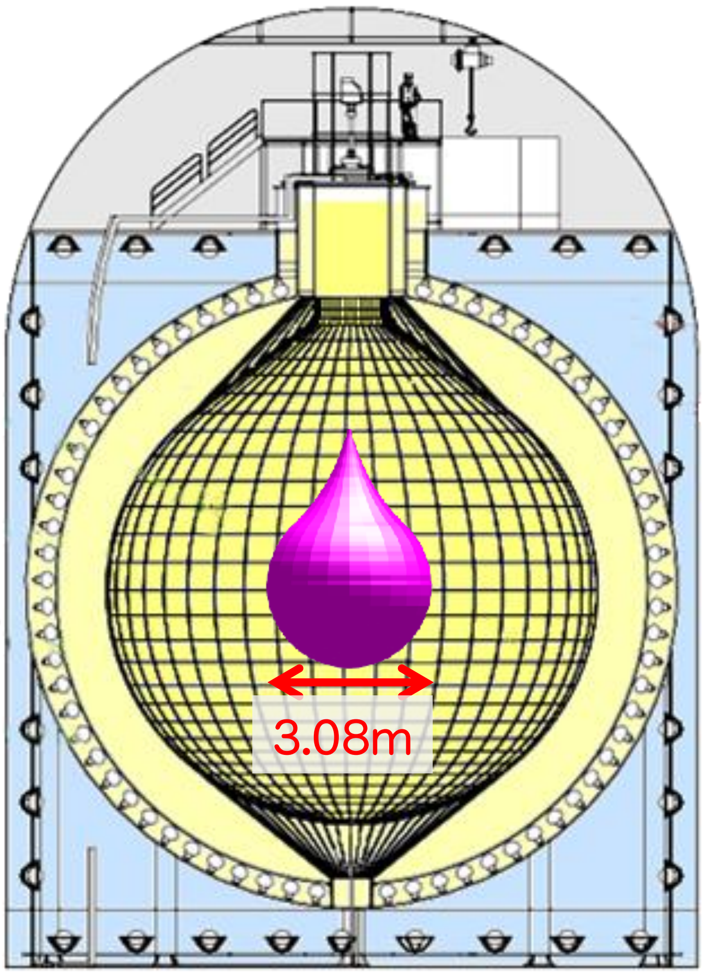
Neutrino Beam (IsoDAR)
- use DAEδALUS injector
- 60 MeV proton beam to Be
- neutrons from Be
- $^{7}Li(n,\gamma)^{8}Li$
- ^{8}Li beta decays: 10^{22} / yr

Dark Matter

NaI Crystal (KamLAND-PICO)
- verify DAMA/LIBRA results
- ~1000 kg NaI crystal
- U 1.1 ppt, Th 0.6 ppt crystal already developed

KamLAND-Zen Project

Searches for $0\nu\beta\beta$
with 380 kg of 91.7% Enriched ^{136}Xe (Q=2.458 MeV)



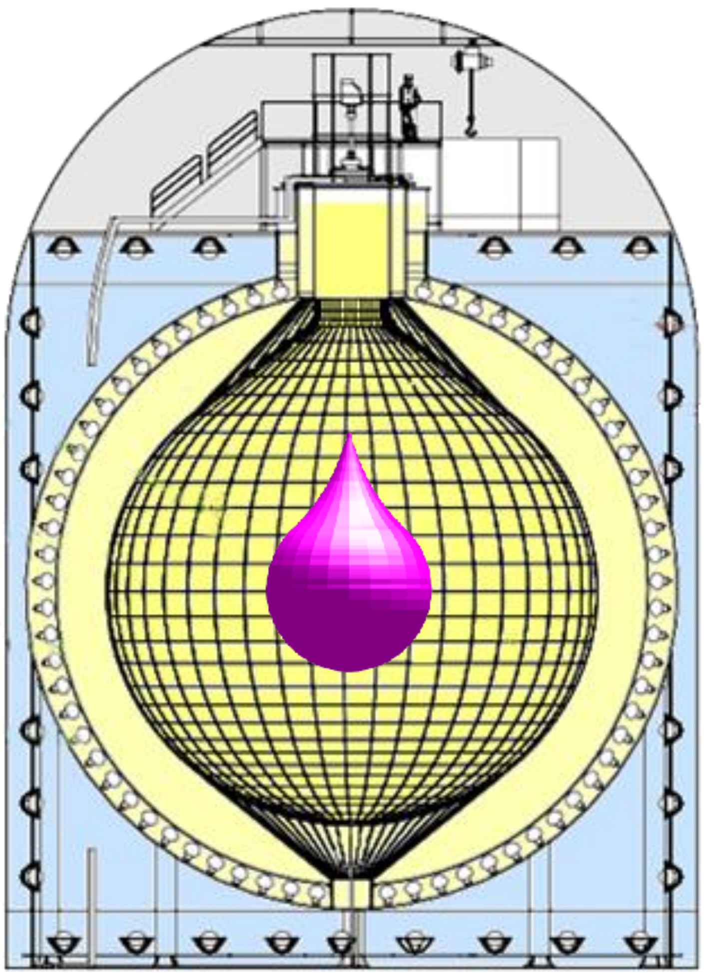
- ✓ 3 wt% Xe in liquid scintillator
- ✓ contained in 1.54m radius inner balloon
- ✓ balloon replaceable, Xe extractable

- ✓ make use of KamLAND facilities
  - purification system
  - PMT, ATWD digitizer, analysis tools, ...
- ✓ can live with KamLAND (reactor & geo)

- ✓ No BG particle escape
  - no 2.6 MeV peak from ^{208}Tl
  - Bi-Po cascade decay tagging

Drawbacks:
- poor energy resolution (~4% @ 2.6 MeV)
- no β / γ discrimination

KamLAND-Zen: Key Developments



Xe-loaded Liquid Scintillator

- Density balance
- Light-yield matching to outer LS
  - Xe reduces light-yield by ~10%
  - increase PPO
  - density ...

Inner Balloon

Not commercially available, developed for ZEN

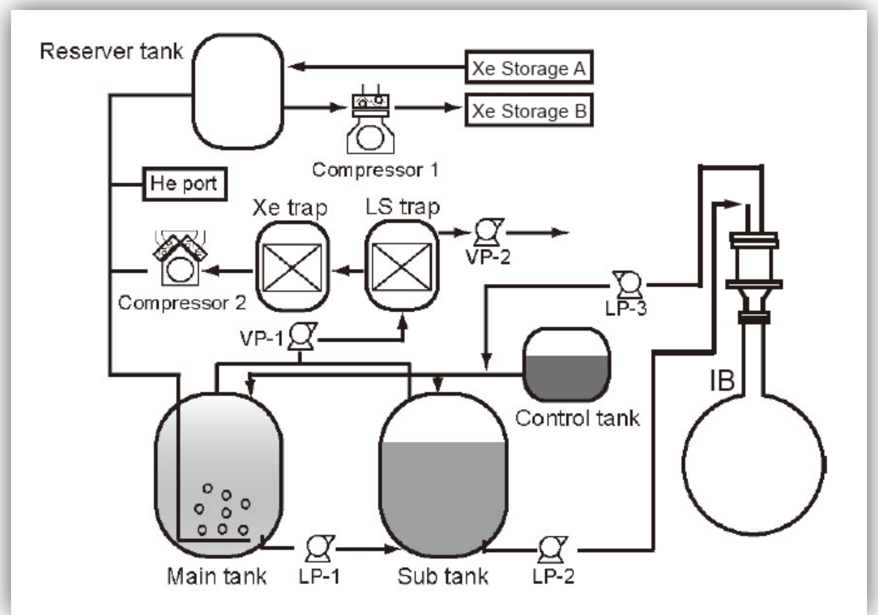
- Clean: U/Th/K $\sim 10^{-13}$ g/g
  -no filler, no lubricant, no glue
- Thin: 25 μm for Bi-Po α-tagging
- Welding by heat-only (no glue)
- Xe-gas tight (<220 g/yr)
- Transparent: 99.4% @400nm

Inner-Balloon Fabrication & Installation

Ultrasonic cleaning in a super clean room

Heat-only welding of Nylon (no glue at all) developed for the Zen Balloon

Xe Handling Facility



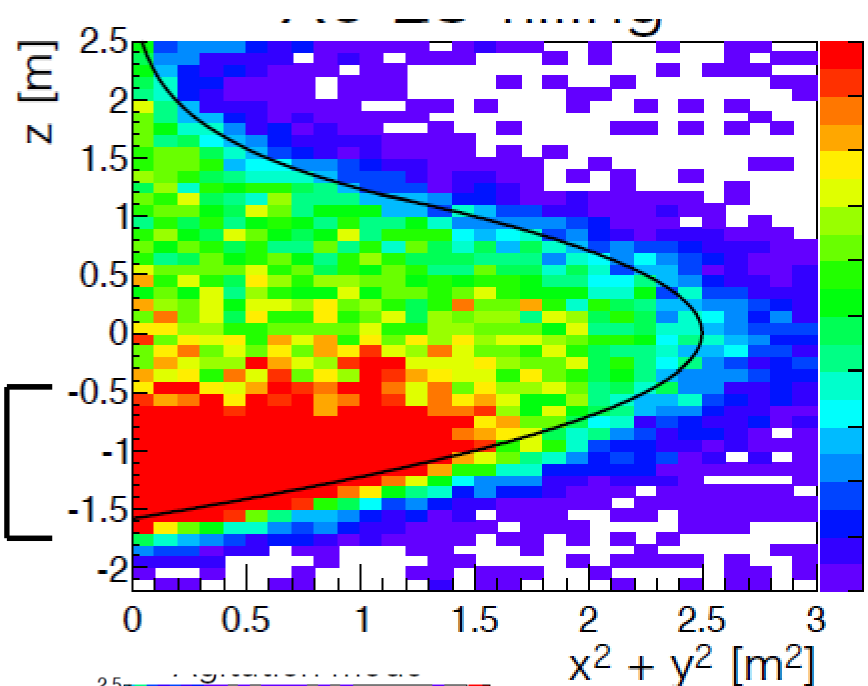
- ✓ Xe Dissolving by bubbling
- ✓ Xe Extraction by degassing & bubbling with scintillator cold trap
- ✓ Precise Control & Monitor (0.005 ~ 0.01 %) by density measurement & mass balance
- ✓ 91.7% Enriched ^{136}Xe, 610 kg in hand

Xe-LS Filling into Inner-Balloon

Inner balloon was initially filled with normal LS (no Xe)

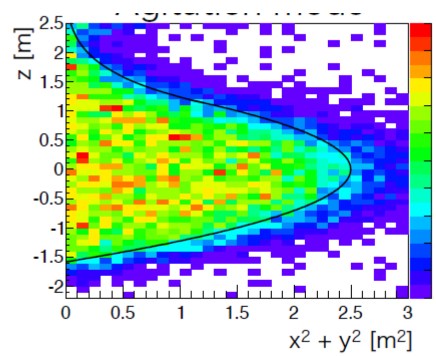
Then Xe-LS was fed from bottom with slightly higher density (+0.035%)

Initial Rn contamination makes newly filled Xe-LS very visible



^{enr}Xe 330 kg filled (enrichment 91.7%)

Mix the whole volume by few more full circulation

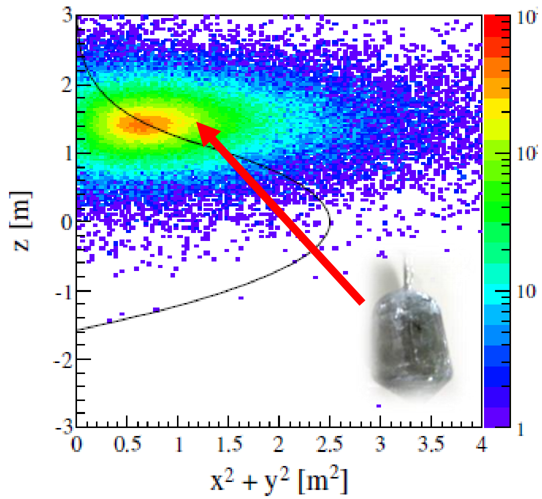


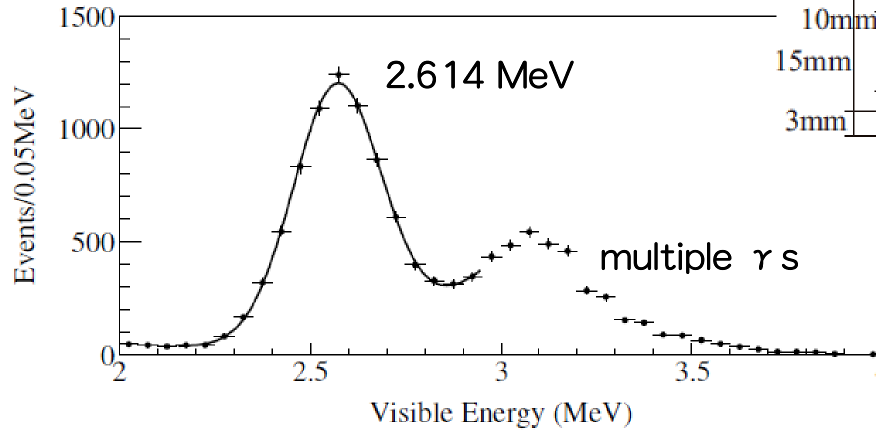
Start data taking on Sep 24th 2011

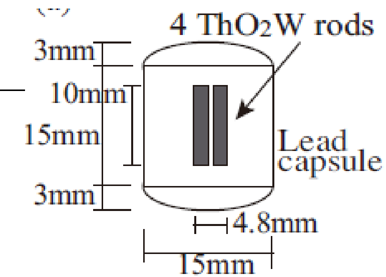
(only two years from the first Zen funding)

Energy Calibration

ThO_2W Source (2.6 MeV γ from ^{208}Tl)



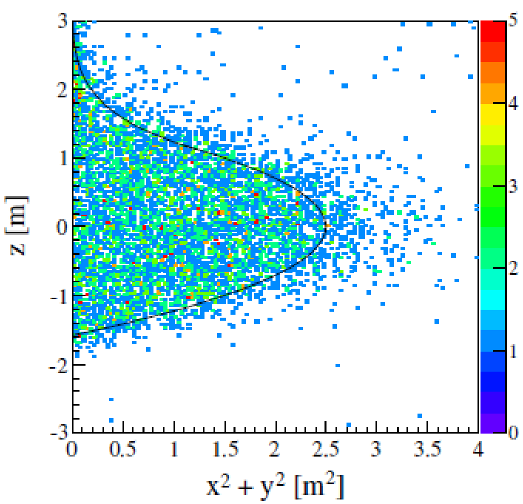


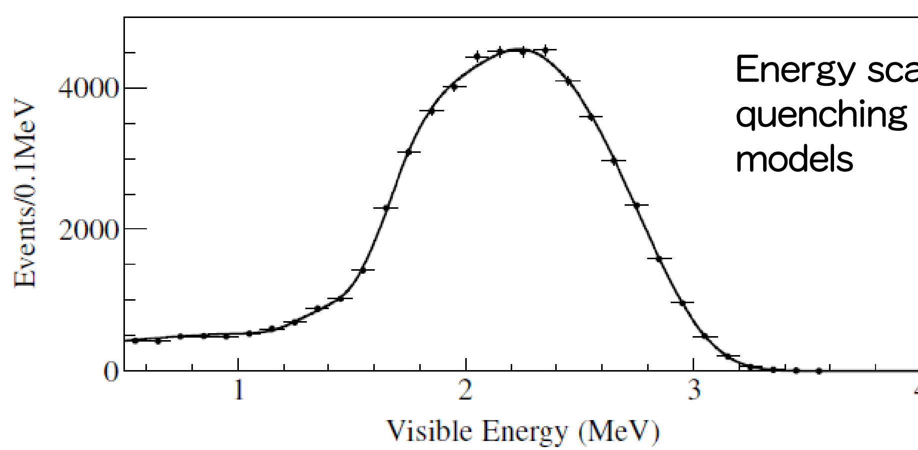


$\sigma = (6.6 \pm 0.3)\% / \sqrt{E(\mathrm{MeV})}$

(4.1% @ 2.6 MeV)

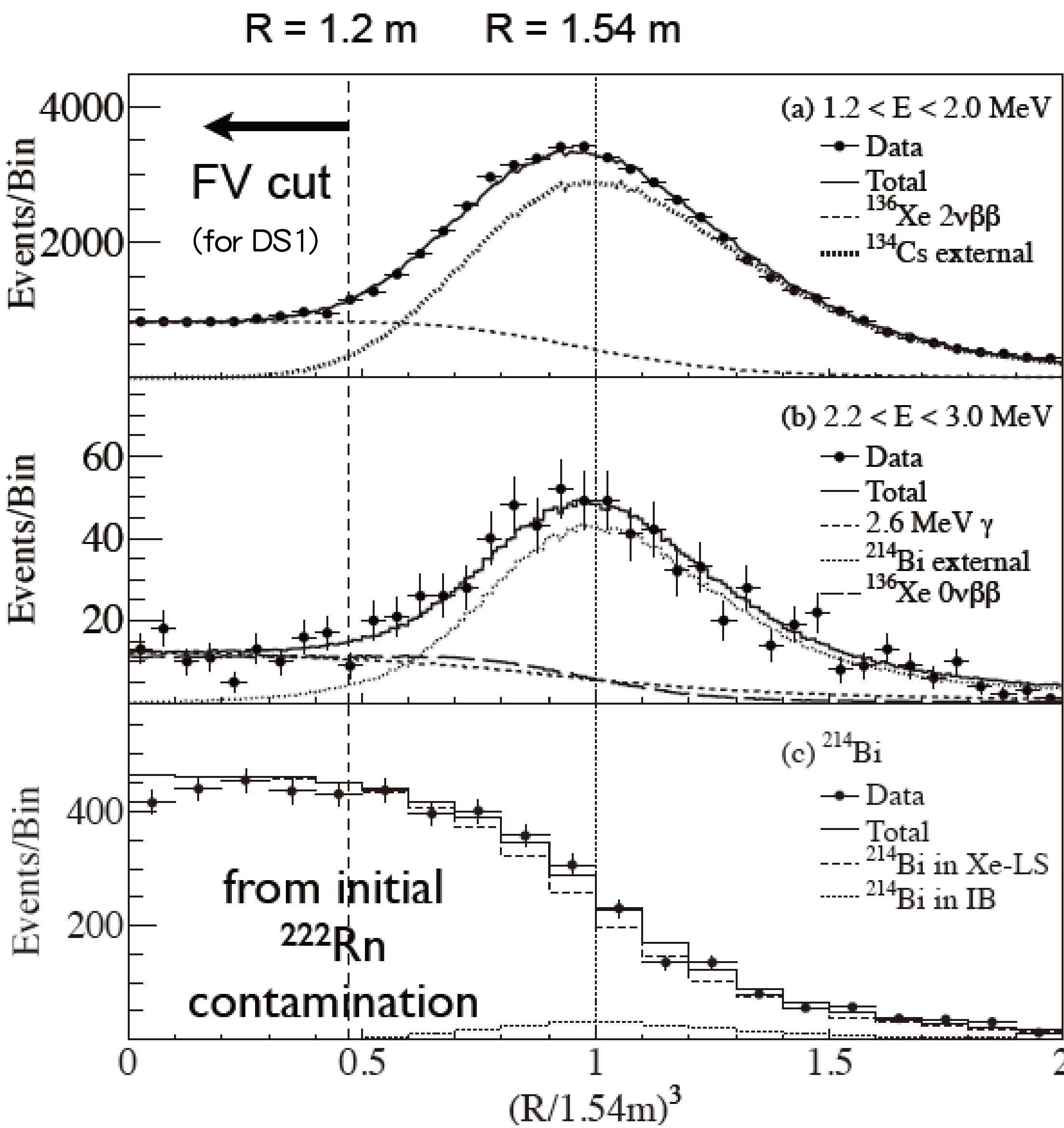
^{214}Bi from initial contamination ($\beta + \gamma$)

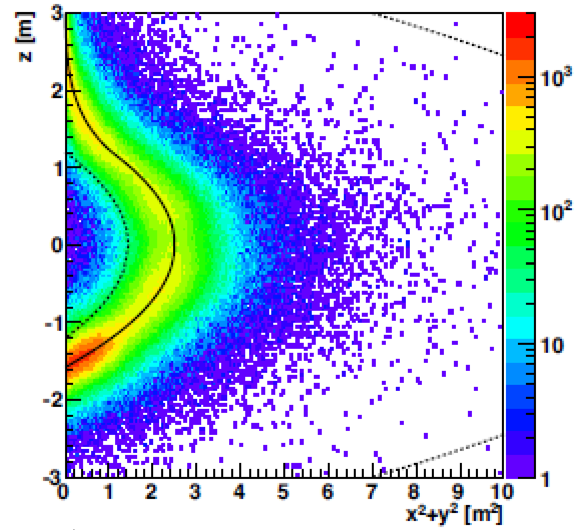




Energy scale includes quenching & herenkov models

Fiducial Volume





^{214}Bi in balloon limits FV

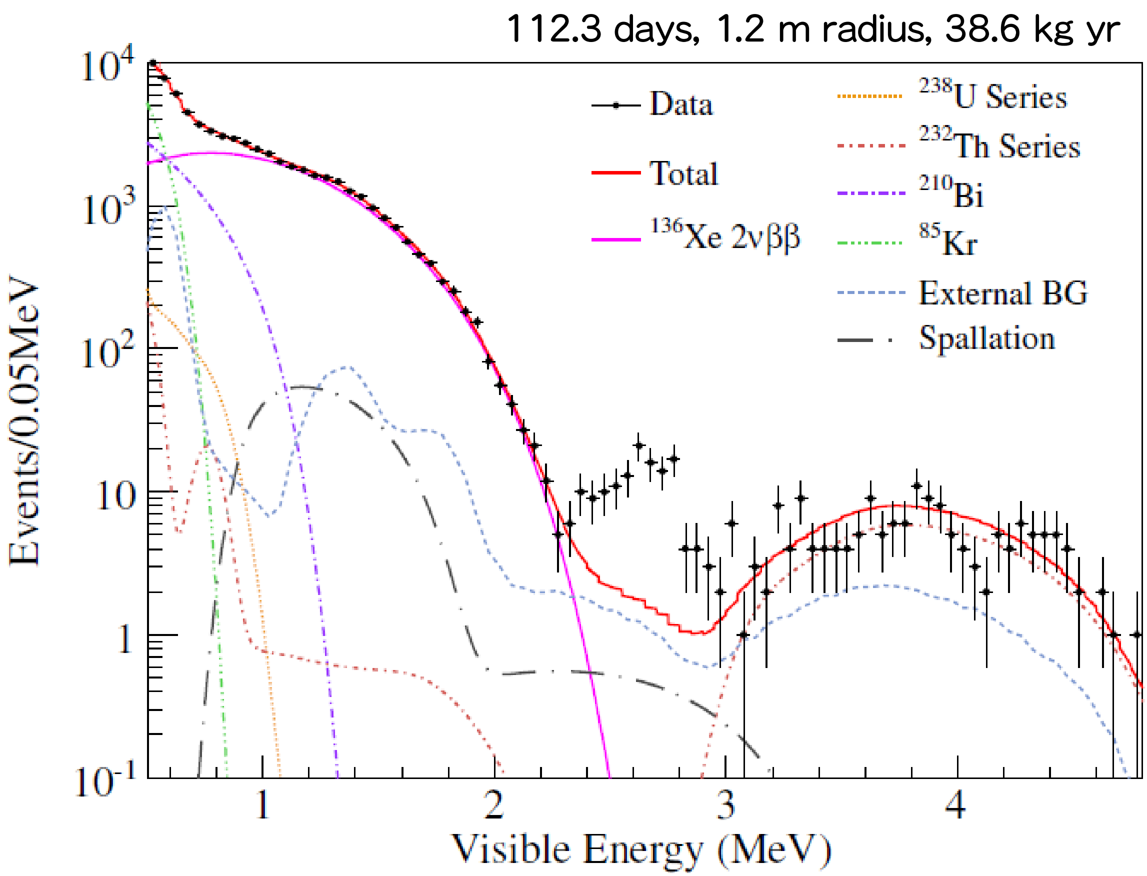
Vertex resolution:
σ ~ 15 cm / √E(MeV)

FV ratio estimated with uniformly distributing initial ^{214}Bi

⇒ 3.9% / 4.1% FV error
(DS1) (DS2)

All other syst. errors: <1%
(^{136}Xe amount, efficiency, etc)

Energy Spectrum & 2νββ Half Life



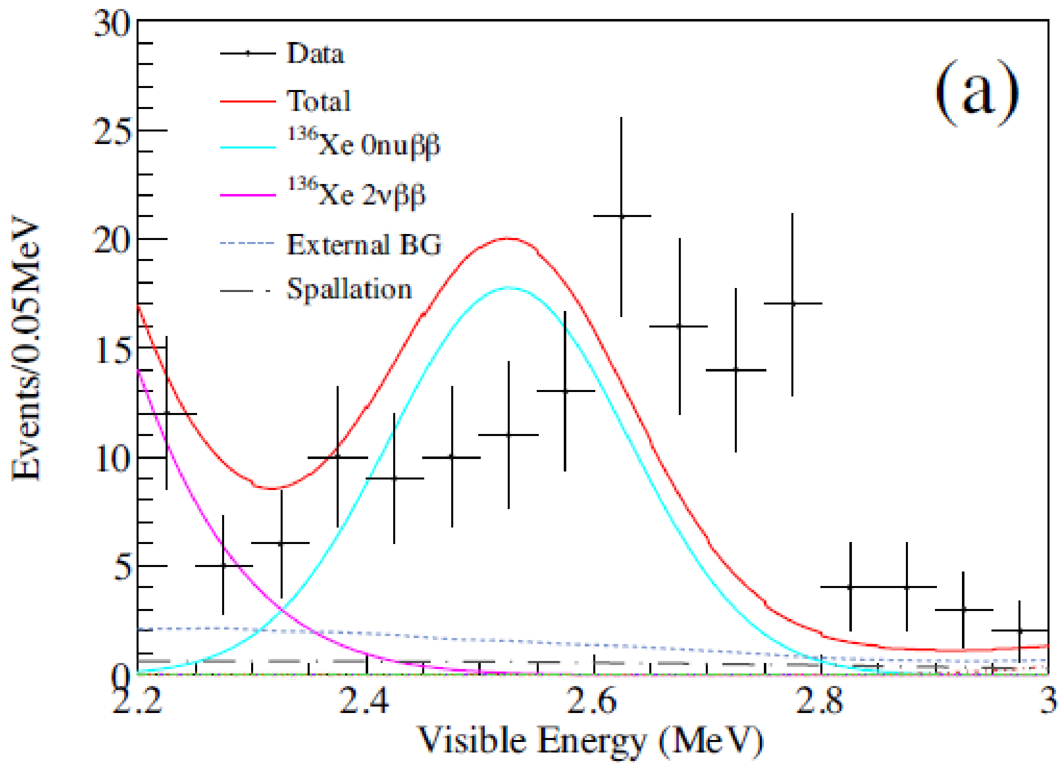
$$T_{1/2}^{2\nu} = 2.38 \pm 0.02\ (\mathrm{stat}) \pm 0.14\ (\mathrm{syst})\ \times 10^{25}\ \mathrm{yr}$$

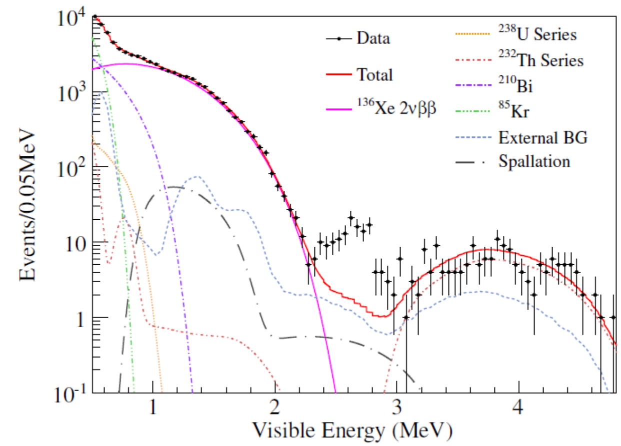
Consistent with EXO-200

Phys.Rev.C 85 045504 (2012)

The Peak is not 0νββ

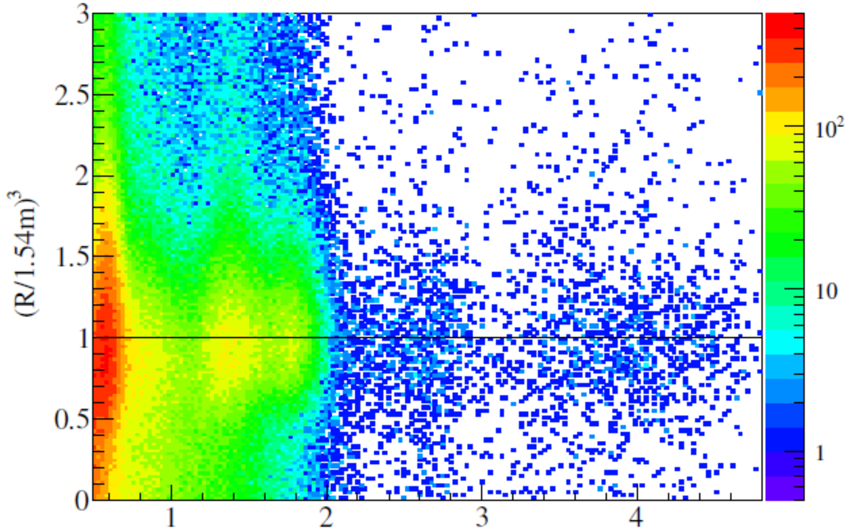
(and not ^{208}Tl)

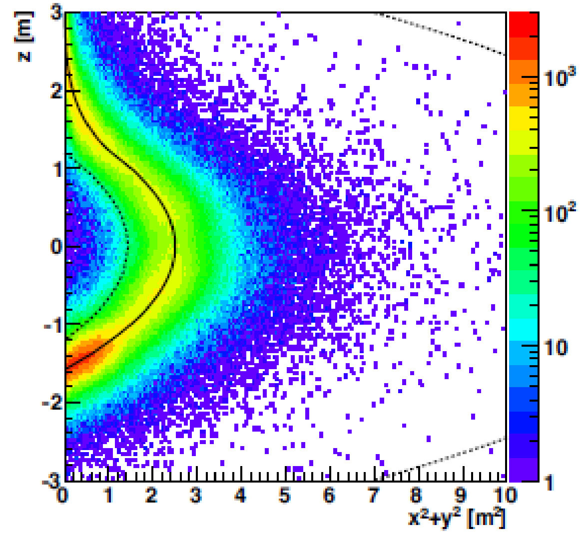


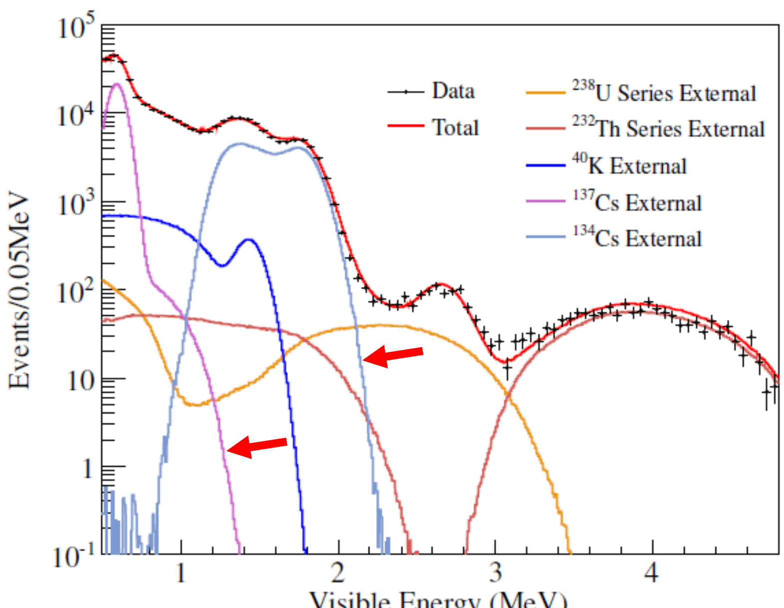


0νββ Spectrum shape is inconsistent at >8 σ

Balloon is Contaminated with Fukushima Fallout





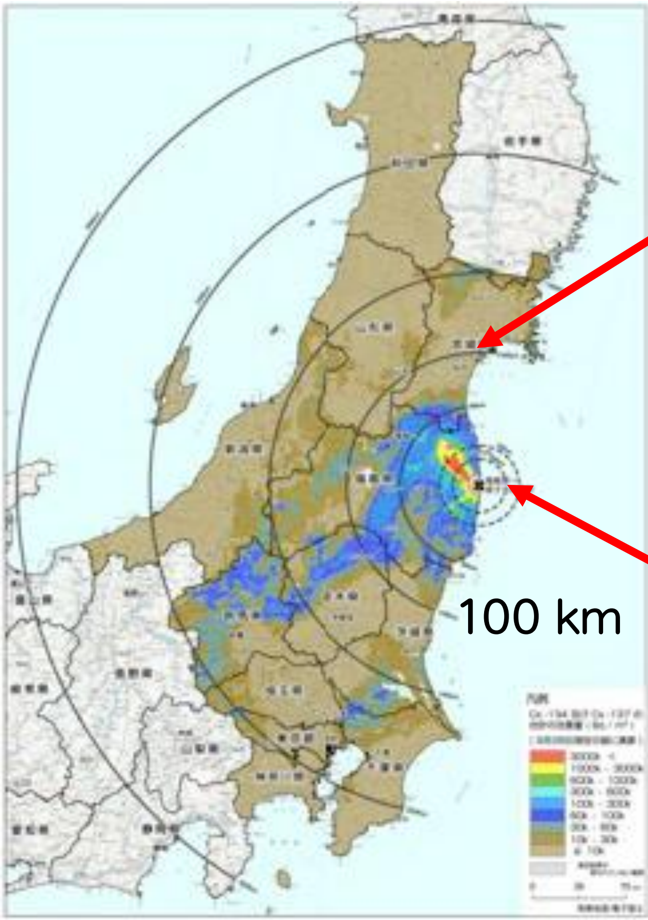


^{137}Cs and ^{134}Cs dominate the balloon activity

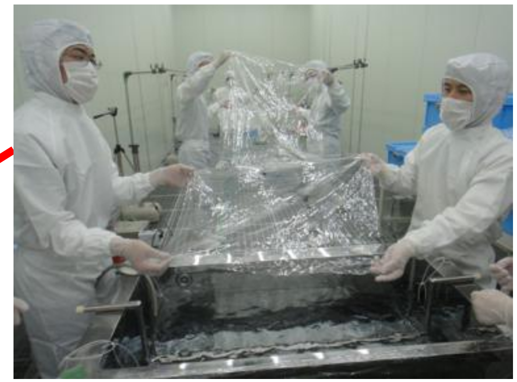
^{134}Cs / ^{137}Cs ~ 0.8, consistent with fallout composition

Cs is not soluble in scintillator

Balloon is Contaminated with Fukushima Fallout



Sendai, May ~ Aug 2011



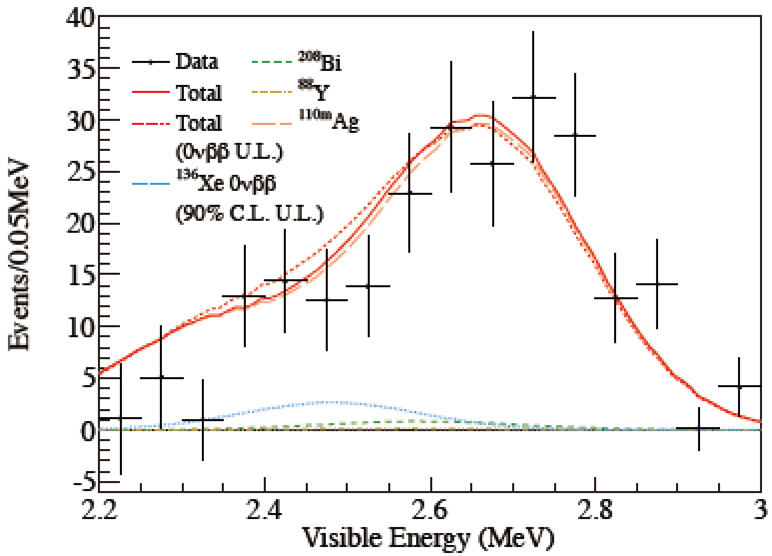
Fukushima, Mar 2011

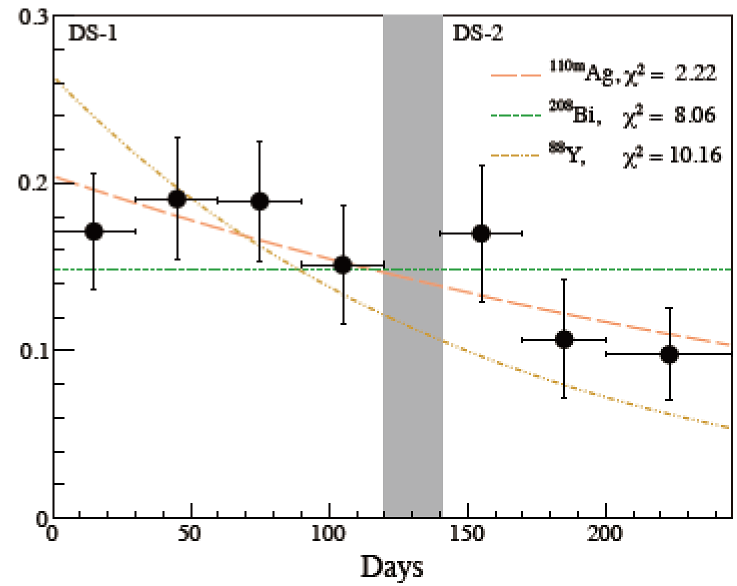
Fallouts detected in Sendai Soil:

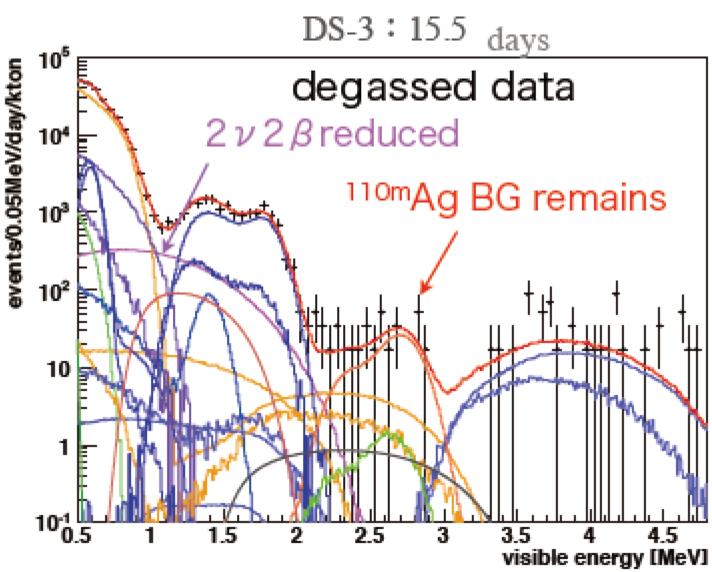
^{134}Cs, ^{137}Cs, ^{110m}Ag, ^{129m}Te, ^{95}Nb, ^{90}Y, ^{89}Sr

→ all included in spectrum fit

~1000 atoms of ^{110m}Ag in Volume







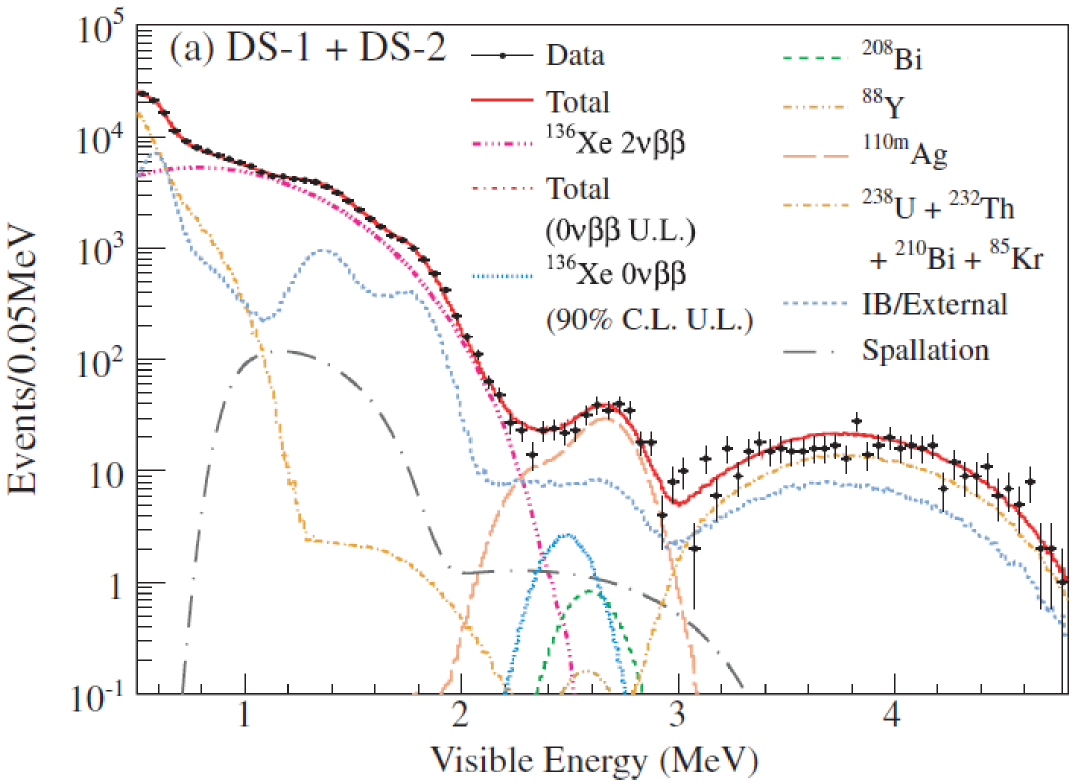
✓ Spectrum most consistent with ^{110m}Ag
(^{208}Bi, ^{88}Y do not fit well, but not excluded)

✓ Decay-time consistent with ^{110m}Ag
($\tau_{1/2}$: 250 days)

✓ Peak remains after Xe extraction
→ not from Xe - cosmic-μ interaction

$0\nu\beta\beta$ Limit PRL 110, 062502 (2013)

213.4 days, 98.5 kg yr



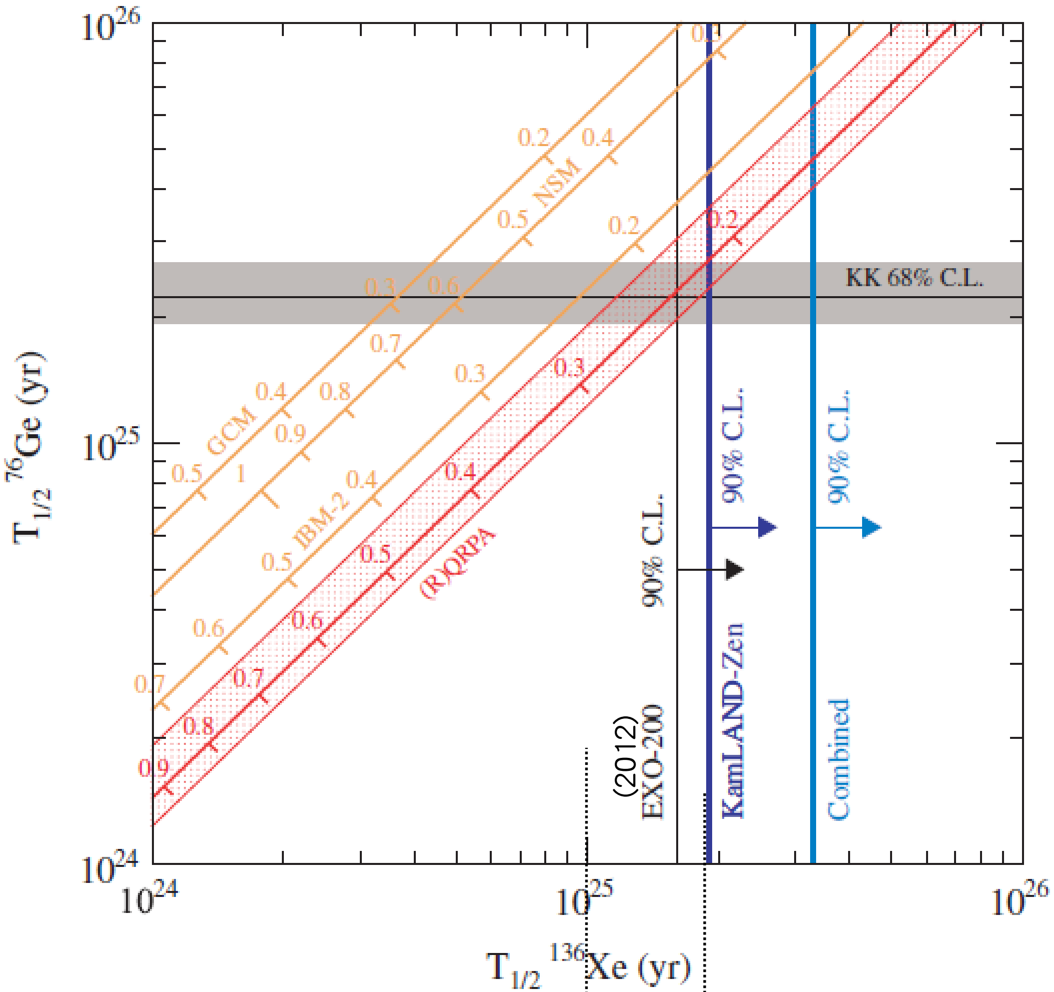
Likelihood fit to binned spectrum

$0\nu\beta\beta$: < 0.16 events/kg/yr

$$T_{1/2}^{0\nu} > 1.9\times10^{25}\ \text{yr} \quad (90\%\ \text{CL})$$
$$\langle m_{\beta\beta}\rangle < 120 \sim 250\ \text{meV}$$

(sensitivity: 1.0×10^{25} yr; we are top 12% lucky)

Combined with EXO-200, Comparison with Ge



KamLAND-Zen: $T_{1/2} > 1.9 \times 10^{25}$

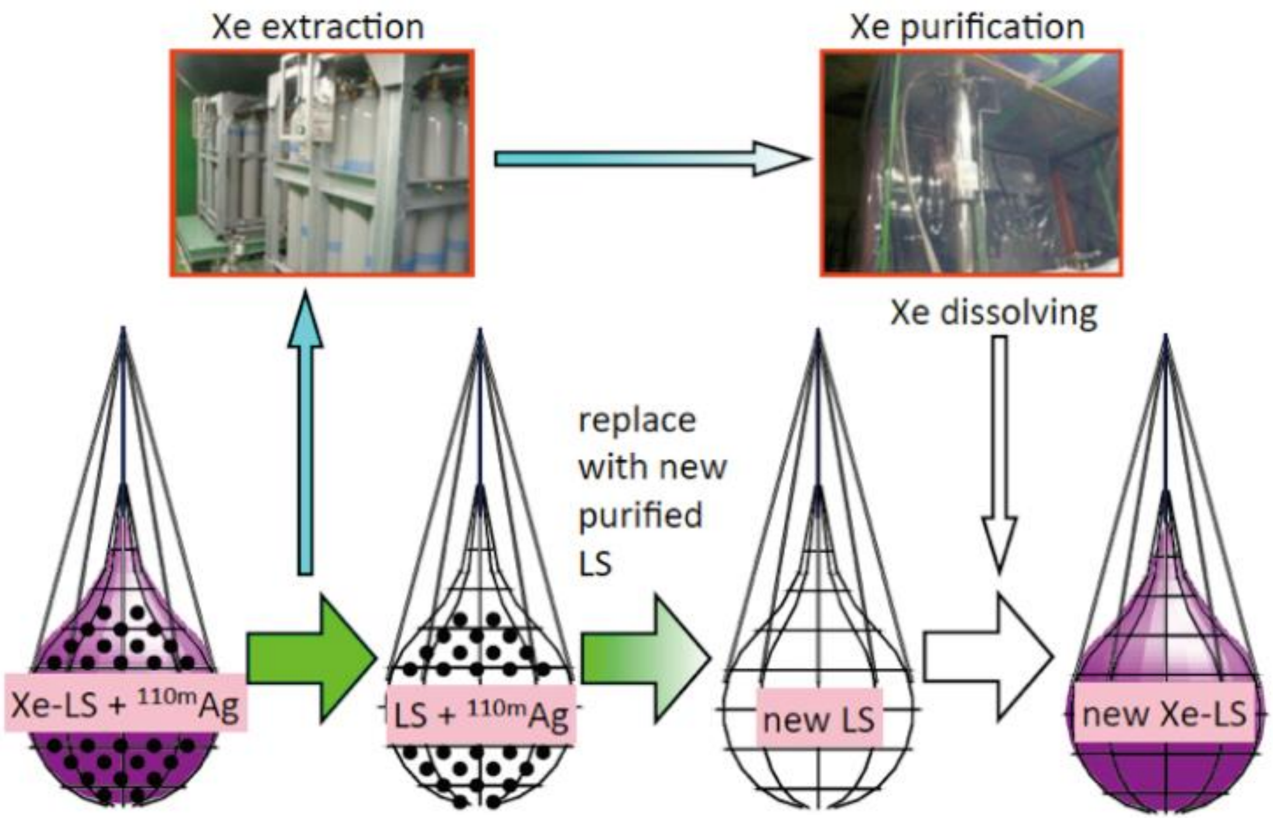
EXO-200 (2012): $T_{1/2} > 1.6 \times 10^{25}$
EXO-200 (2014): $T_{1/2} > 1.1 \times 10^{25}$

KamLAND-Zen + EXO-200 (2014)
$T_{1/2} > 1.6 \times 10^{25}$

EXO-200 (2014) Sensitivity: 1.9×10^{25}

KamLAND-Zen (2013) Sensitivity: 1.0×10^{25}

Ongoing: ^{110m}Ag Removal by Distillation

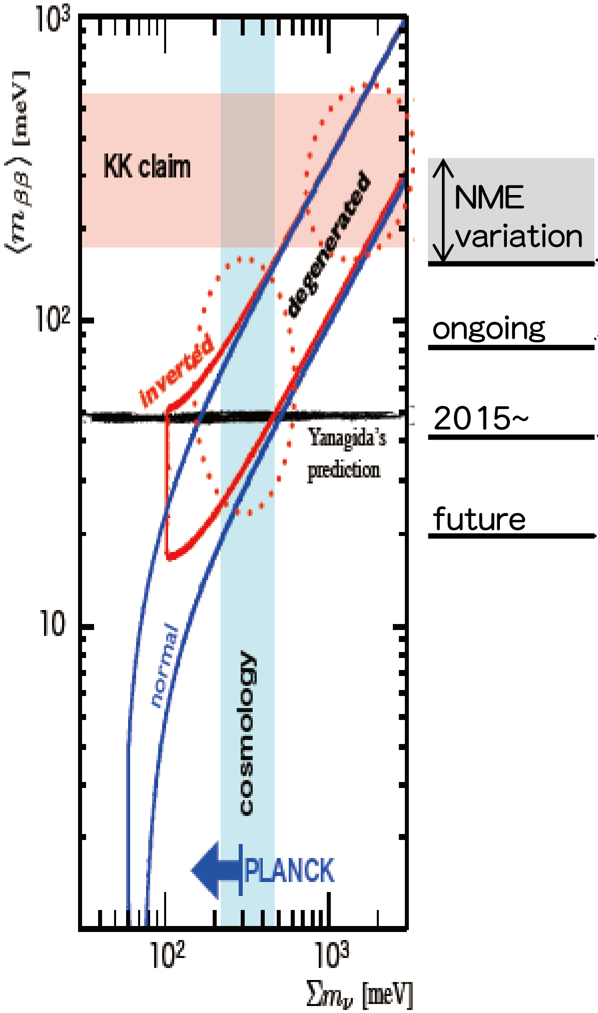


Completed in Nov 2013
>90% of ^{110m}Ag removed

KamLAND-Zen 2nd Phase

Dec 2013 ~, ^{enr}Xe 380 kg (+60 kg to phase 1)

Zen Future: Less Background, More Resolution



KamLAND-Zen

89.5 kg-yr

$\langle M_{\beta\beta} \rangle < 160\text{\textasciitilde}330$ meV

KamLAND-Zen 2nd Phase

^{110m}Ag removal

KamLAND-Zen 3rd(?) Phase

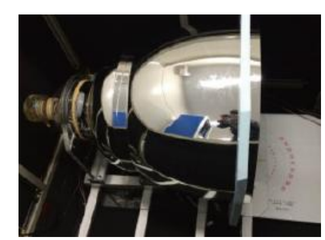
Clean balloon, 600~800 kg Xe

KamLAND2-Zen

PMT: 17 inch → 20 inch
High QE PMT (21% → 29%)
Light collection mirror (x1.8)
High yield scintillator (LAB+PPO, x1.5)

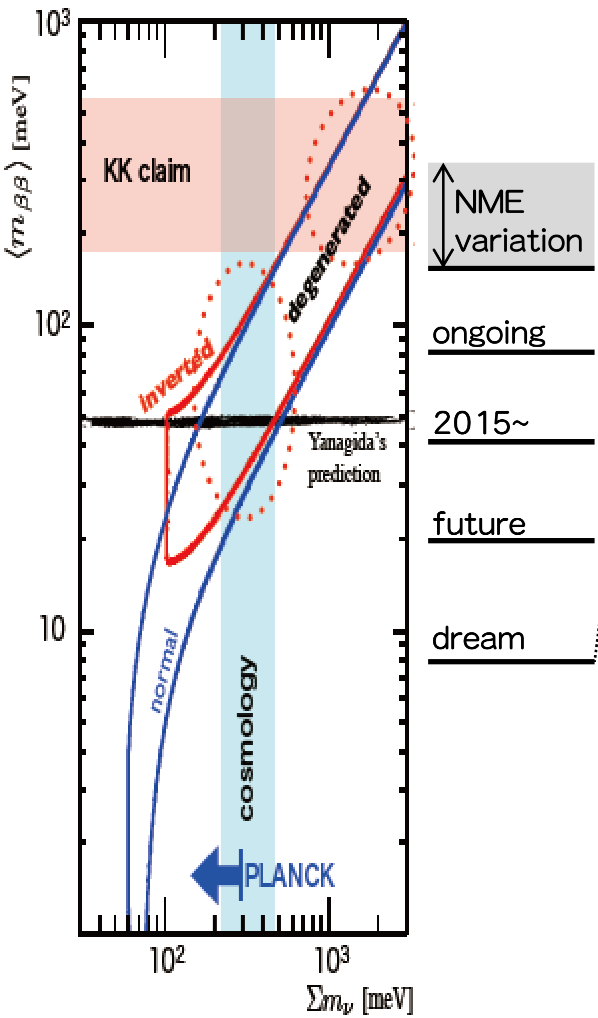
⇩

σ_E: 4.0% → 1.8%
2ν BG: x1/100
~20 meV / 5 yr



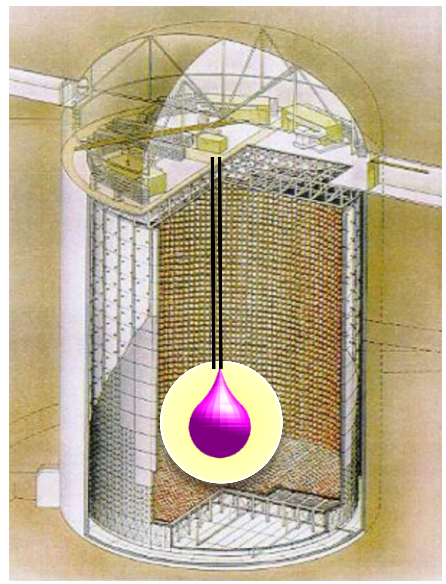
mirror prototype

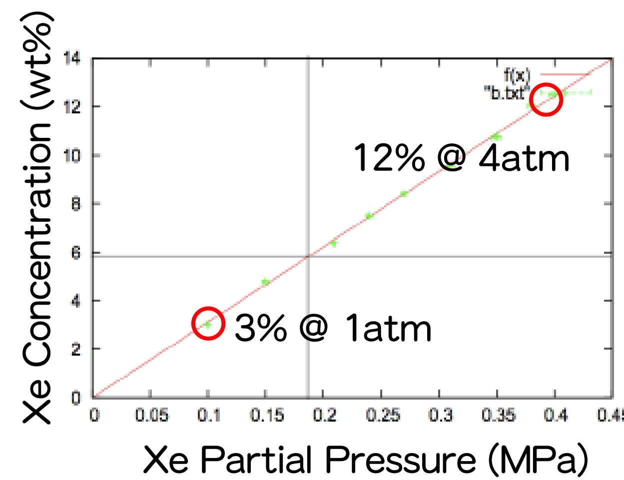
Zen Dream: More Target Density



Super-KamLAND-Zen

Pressurize the Zen Balloon



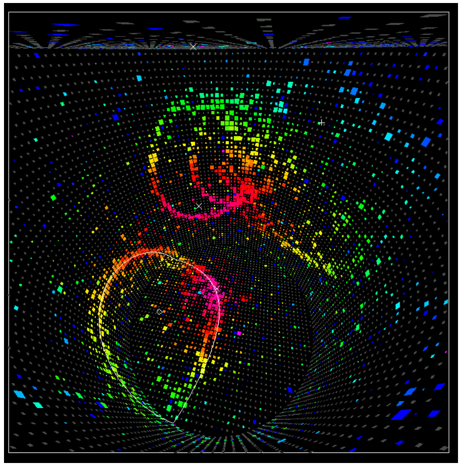


×4 more Xe concentration at 30 m deep

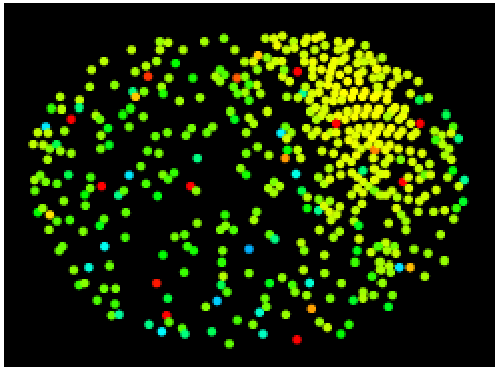
Evolution of KamLAND Scintillation Detector

Water Cherenkov Detector vs Scintillation Detector

Super-Kamiokande



KamLAND



Advantages

Clean (U & Th are ionic)

High light yield (x ~100 of Water Cherenkov)

→ Low energy threshold (~300 eV, limited by ^{14}C)

Delayed coincidence → Selective sensitivity to $\bar{\nu}_e$

Drawbacks

Costly + Layered Shields → Small

No directional sensitivity

Signal pile-up

Mess after cosmic muons (more p.e. + low thresh)

Pile-up Free Electronics (LBL, 2001)

Waveform Recording with ATWD

(ATWD: Analog Transient Waveform Digitizer)

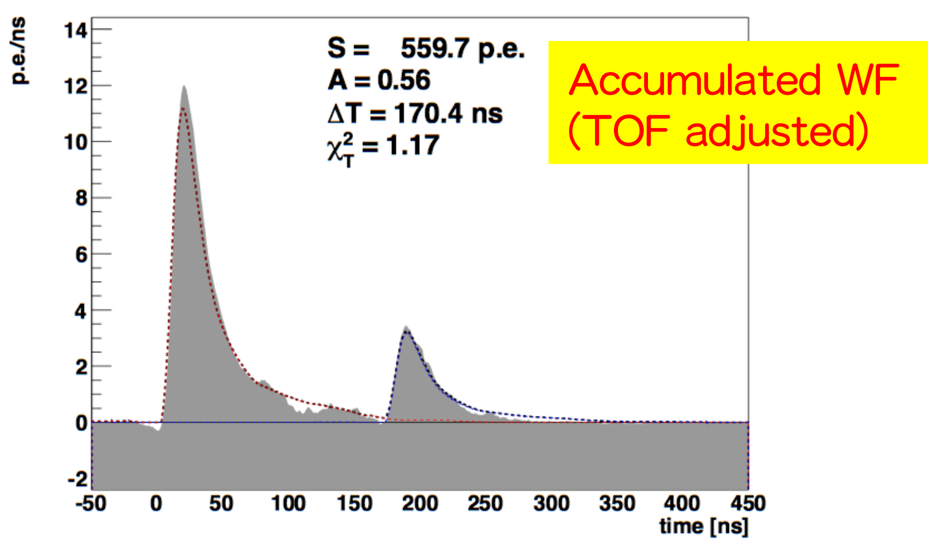
~1.5 ns interval sampling for all channels !!

Two 4-ch ATWDs per PMT

- 4-ch for dynamic range (x20, x4 and x0.5 plus CLK)
- two ATWDs for cascading events

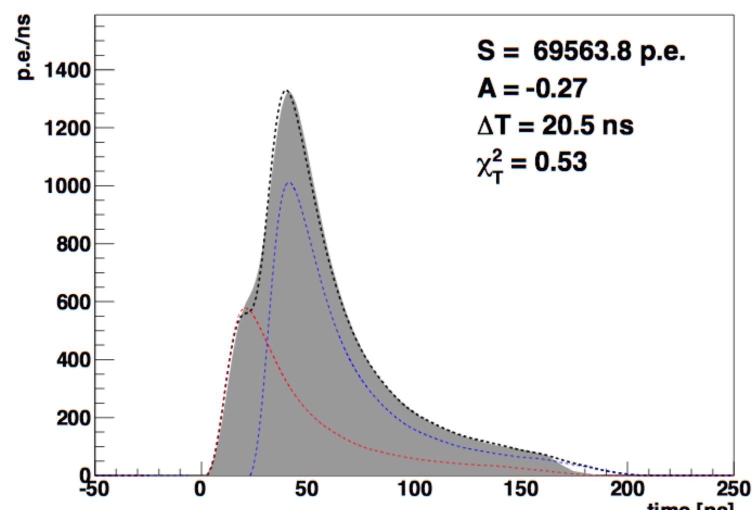
Bi-Po Pile-up Waveform (Data)

$$^{212}\mathrm{Bi} \xrightarrow[64.06\%]{Q_\beta=2.254\mathrm{MeV}} {}^{212}\mathrm{Po}\ (299\mathrm{nsec}) \xrightarrow{Q_\alpha=8.784\mathrm{MeV}} {}^{208}\mathrm{Pb}$$



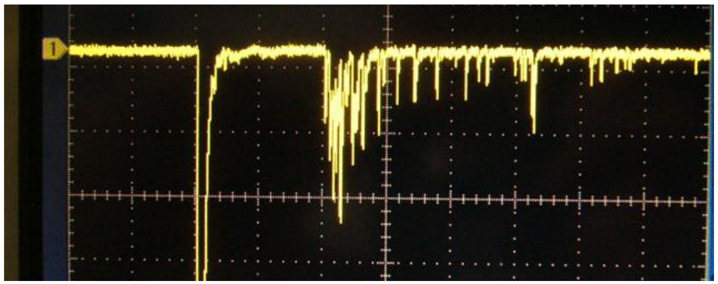
Proton-Decay Waveform (MC)

$$p \to K^+ \bar{\nu}_\mu;\ K^+ \to \mu^+ \nu_\mu;\ \mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$



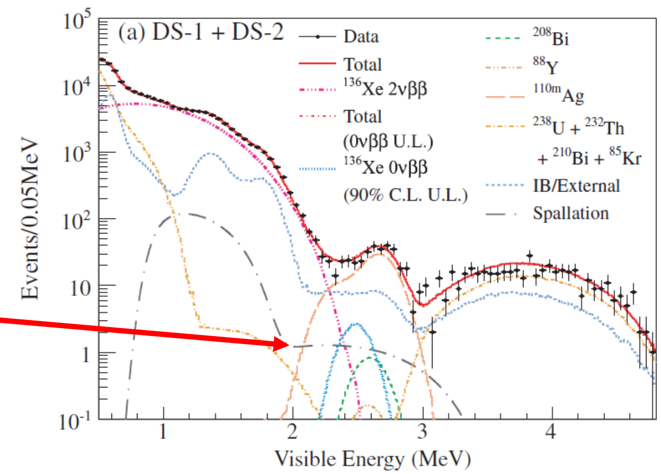
Dead-time Free Electronics (Tohoku, 2009)

Mess After Cosmic Muons



↔
1 μs

- after-pulses: up-to ~100k events in ~100 μs
- neutrons: up-to ~100 events in ~ms



neutrons tells us location of ^{10}C
→ pin-point veto

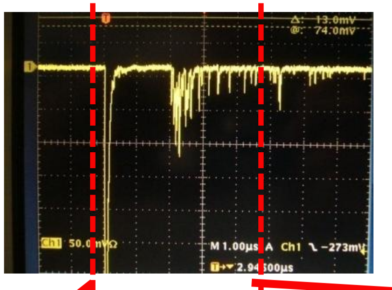
Free-Running FADC + Inline Digital Processing

1 GHz FADC per ch
10 μs ring buffer per ch
>256 event buffer per ch

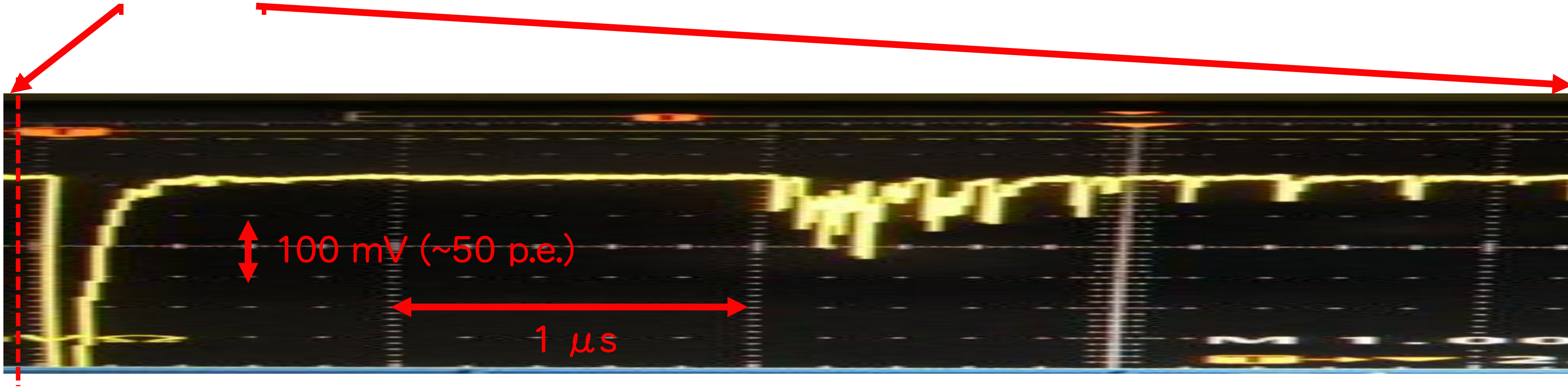
Very similar to the former design except using commercial FADC after 8 years!!

Inline data processing (zero suppression etc)
Onboard processor, serial readout option

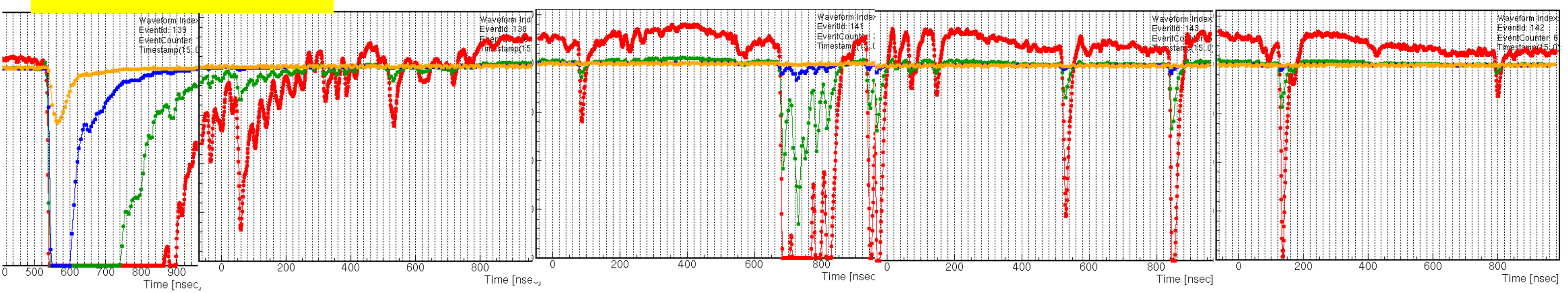
Dead-time Free Electronics



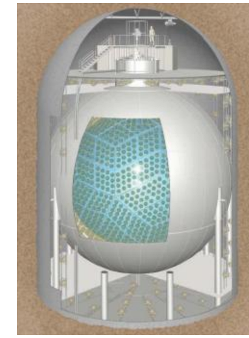
typical *energetic* muon example (~10^5 p.e.)



Recorded Data

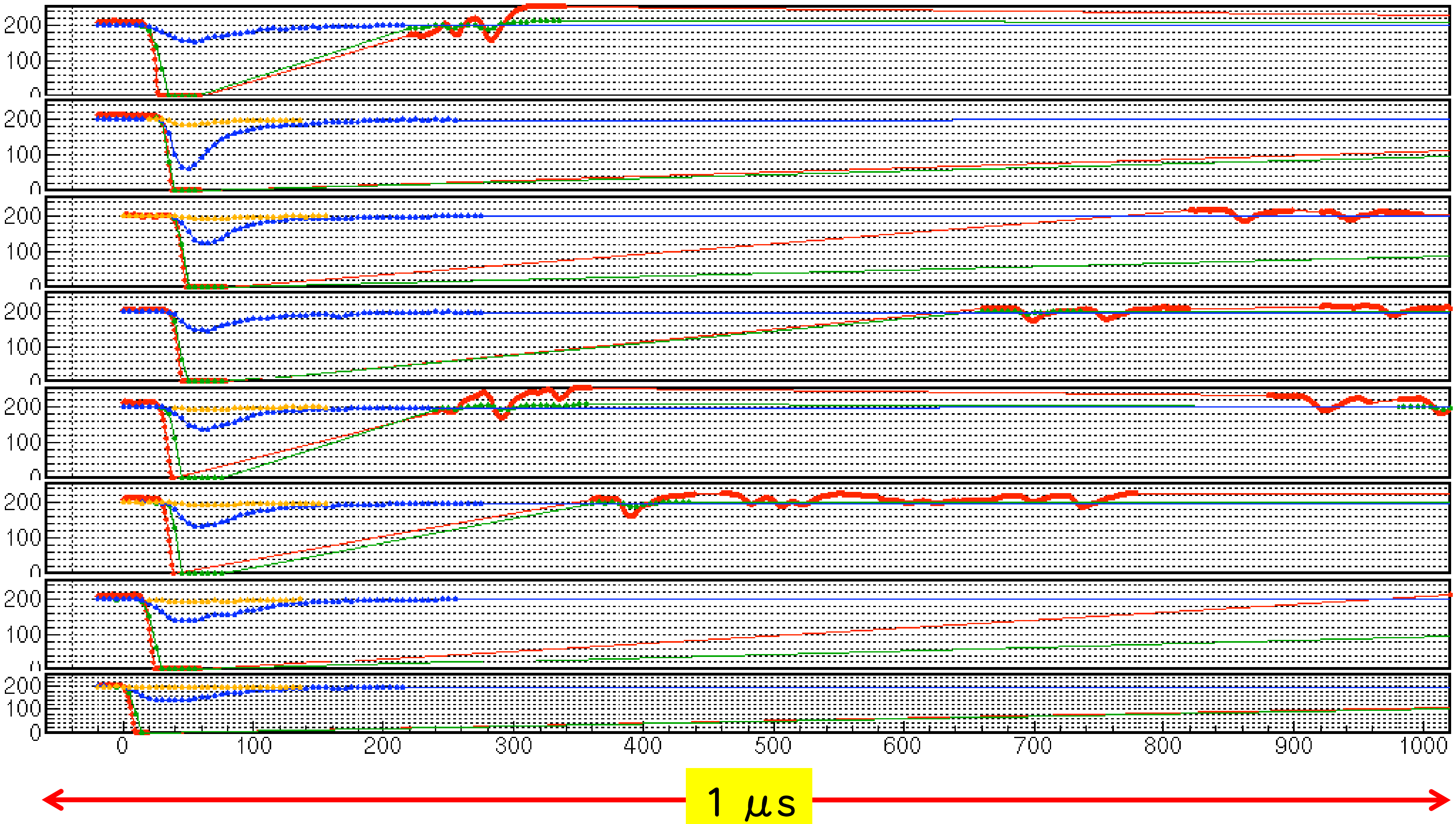


Dead-time Free Electronics



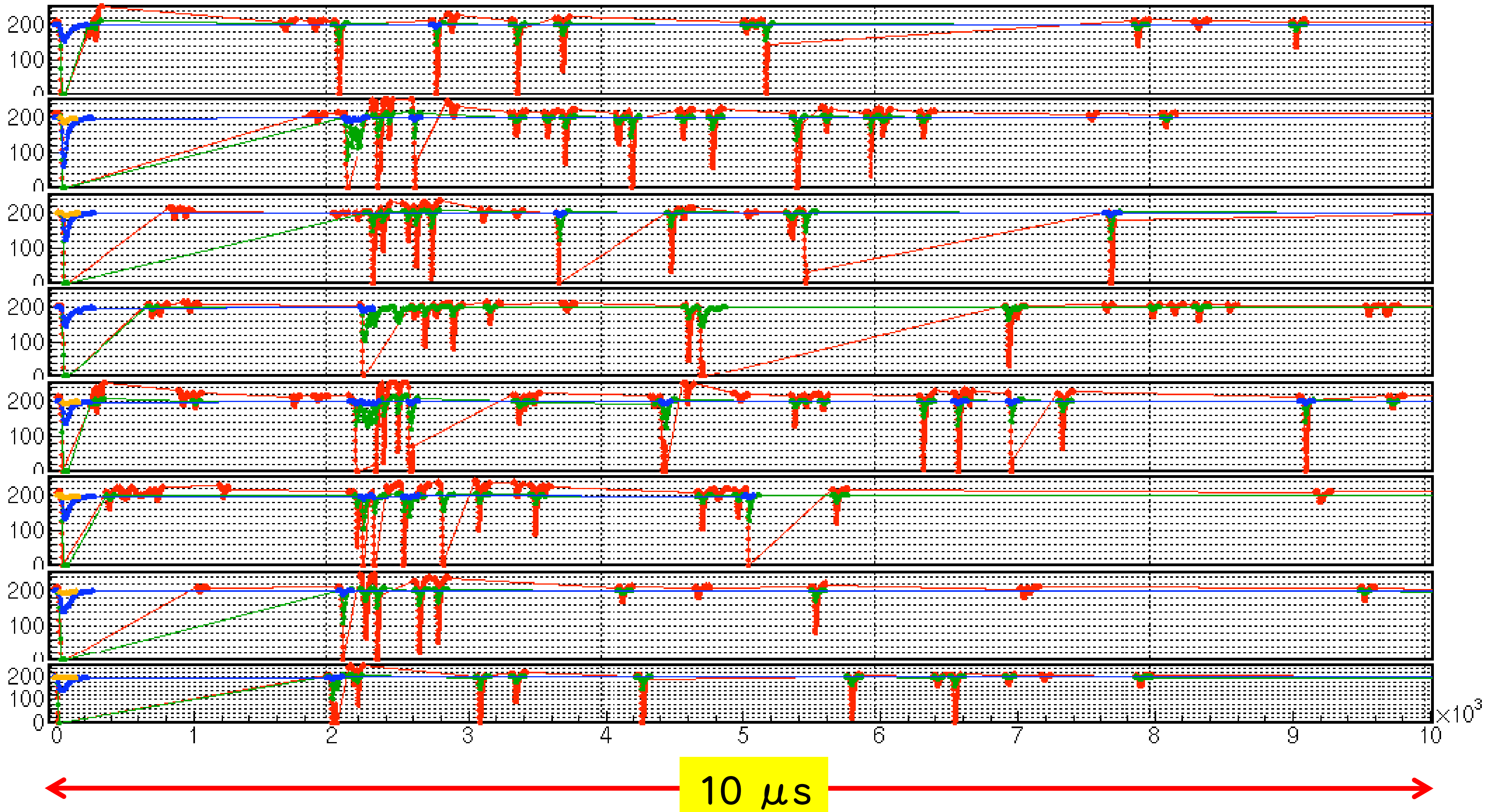
All 1325 channels, with zero-suppression

(only 8 ch are shown below)



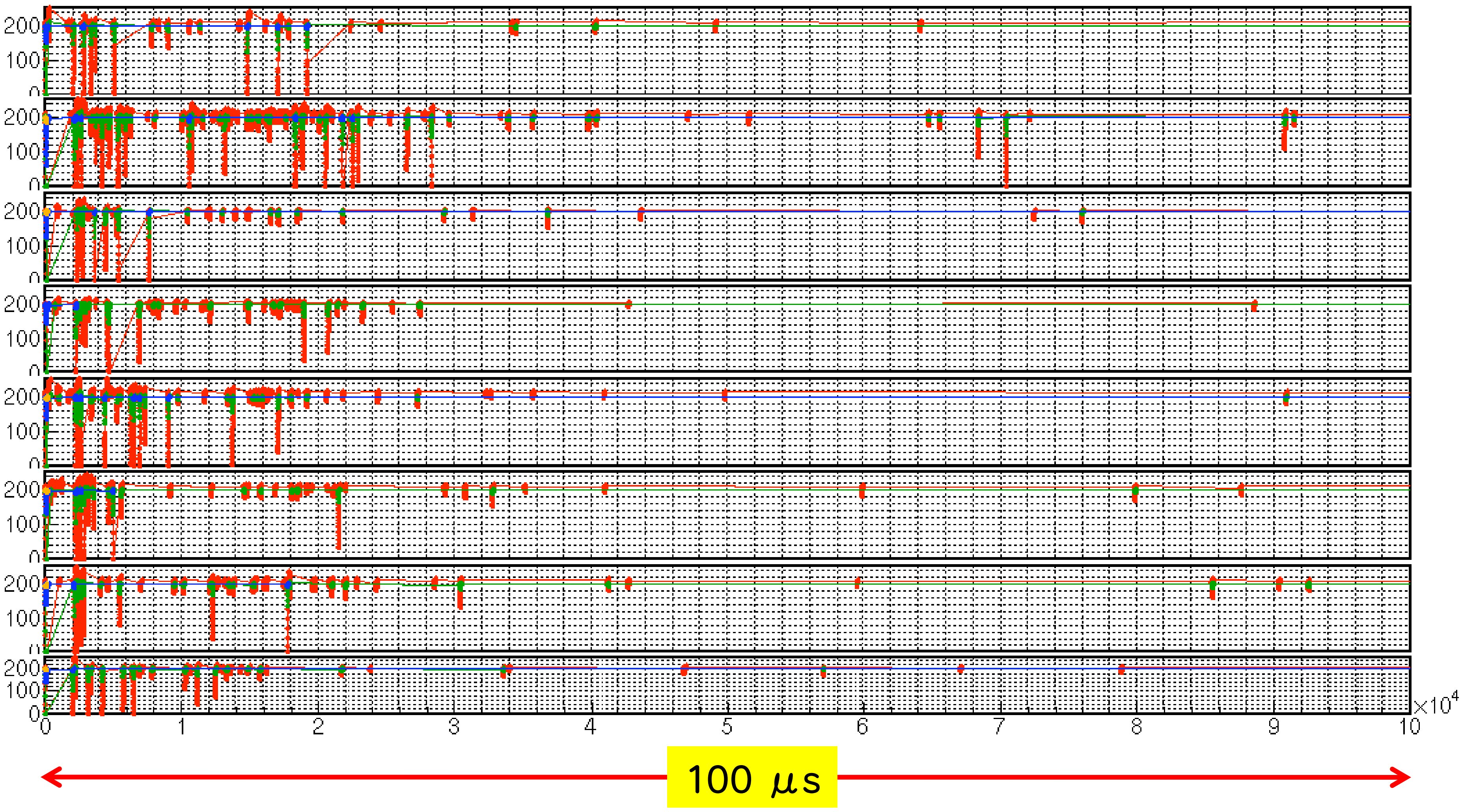
Dead-time Free Electronics

In a longer time range



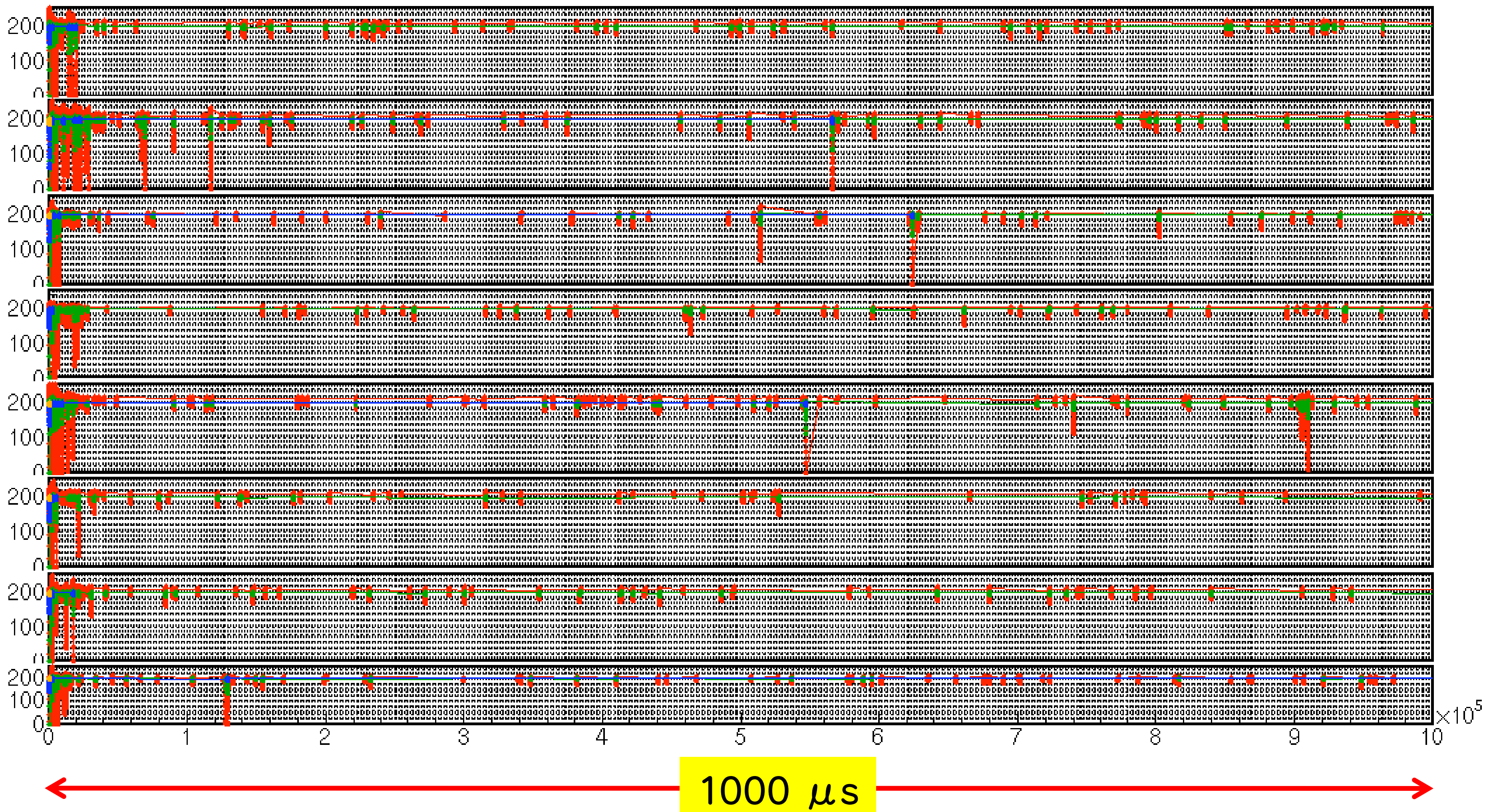
Dead-time Free Electronics

Even longer time range



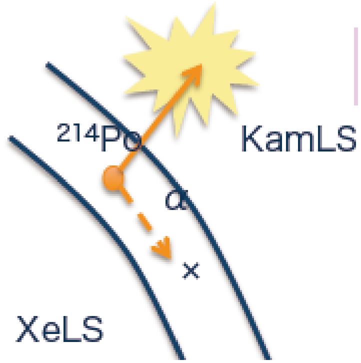
Dead-time Free Electronics

And more !!



Dead-Layer Free Scintillating Balloon (R&D)

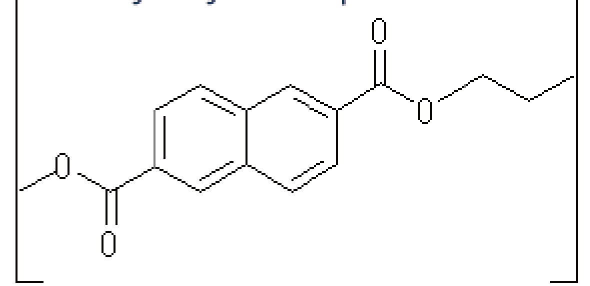
Imperfect Bi-Po tagging
due to balloon *dead-layer*



PEN was found to be scintillating material (2011)

Material	Polyethylene naphthalate	Organic scintillator (ref. [14])
Supplier	Teijin Chemicals	Saint-Gobain
Base	$(C_{14}H_{10}O_4)_n$	$(C_9H_{10})_n$
Density	$1.33\,g/cm^3$	$1.03\,g/cm^3$
Refractive index	1.65	1.58
Light output	~ 10500 photon/MeV	10000 photon/MeV
Wavelength max. emission	425 nm	425 nm

PolyEthyleneNaphthalate



First look at 50 μm-thick PEN film (Tohoku)

✓ Scintillates !!

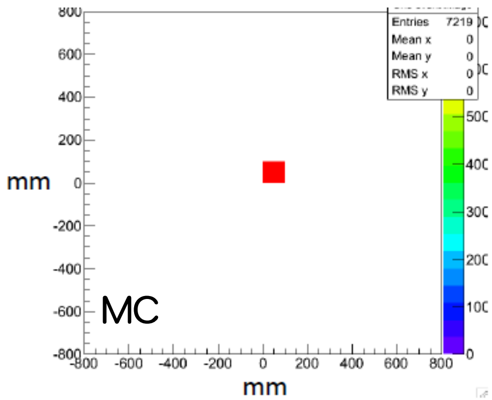
✓ Clean enough, Weld-able, chemically compatible with LS

Detail studies ongoing

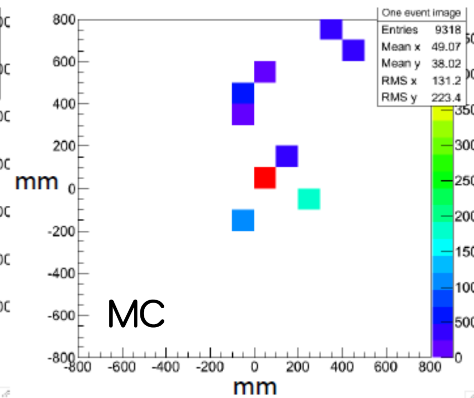
Scintillation Imaging (R&D)

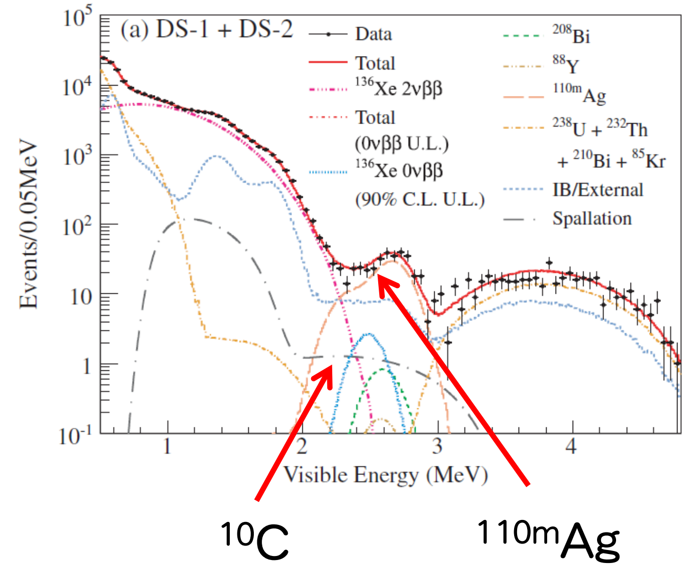
Particle Identification using Event *Size*

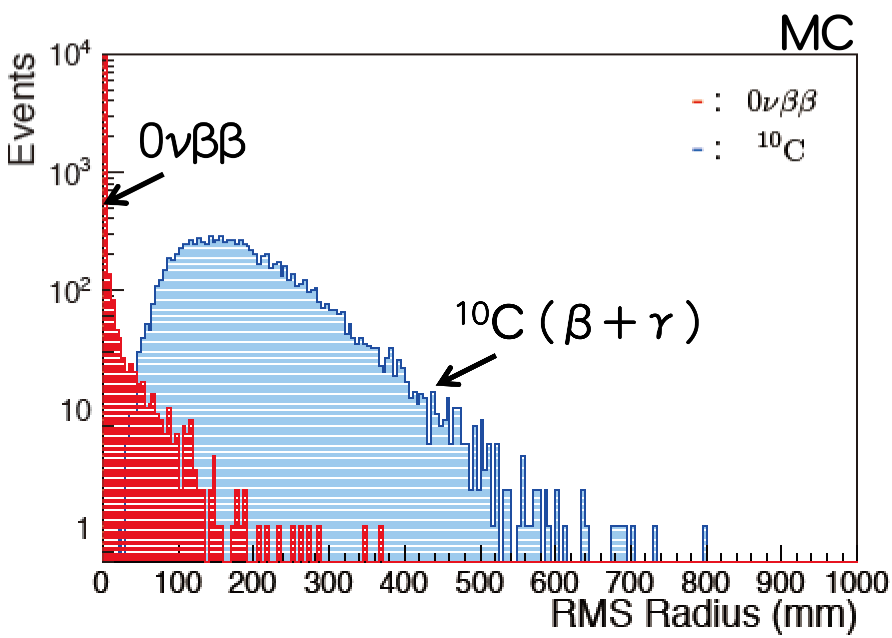
$0\nu\beta\beta$

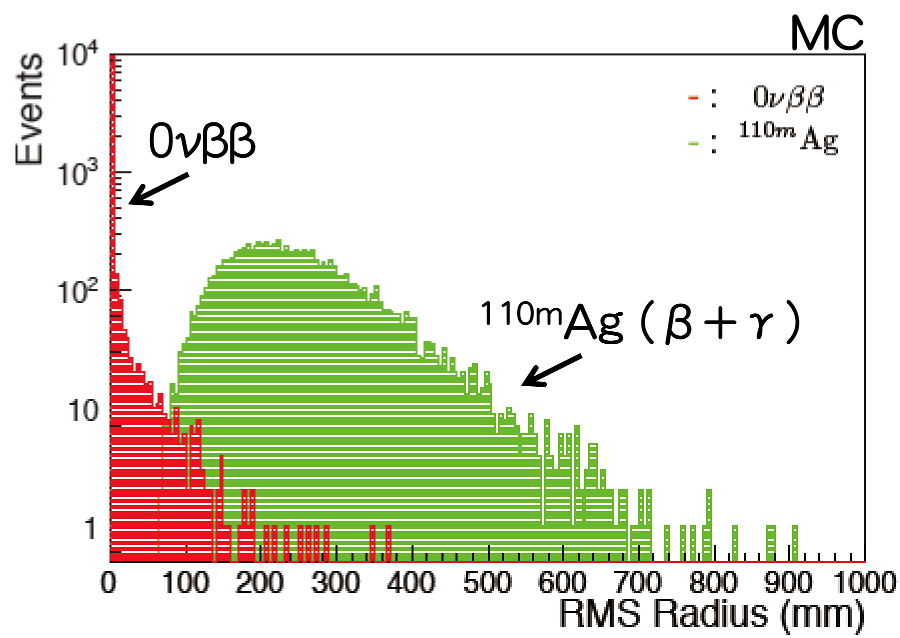


$^{10}C\ (\beta+\gamma)$



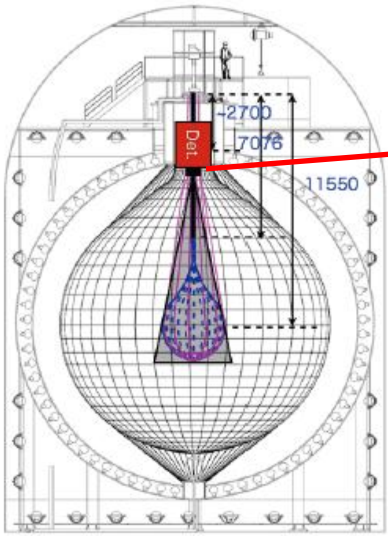


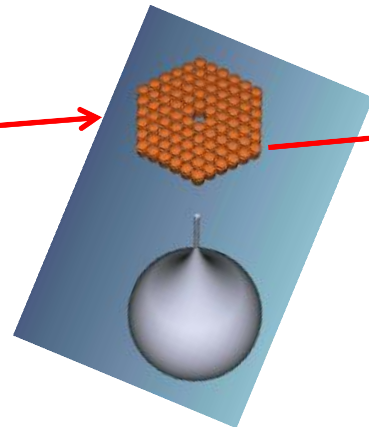




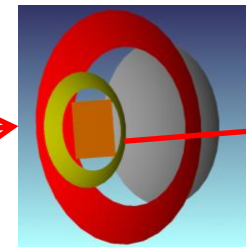
Scintillation Imaging (R&D)

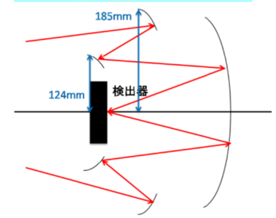
Optics and Readout Design (Tohoku)



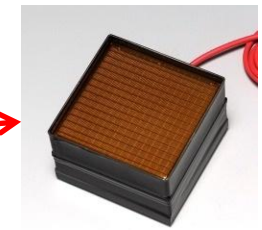


90 imaging units
viewing mini-balloon



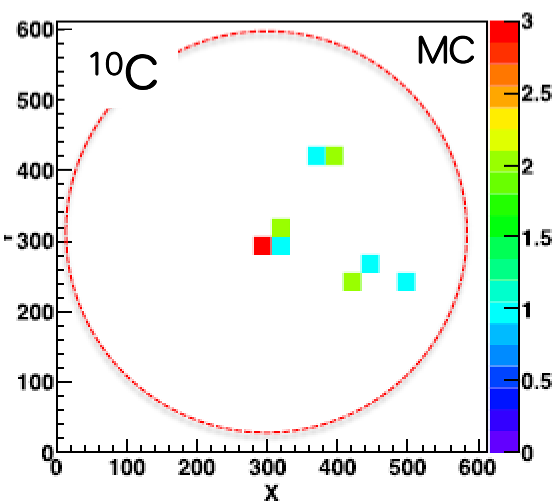


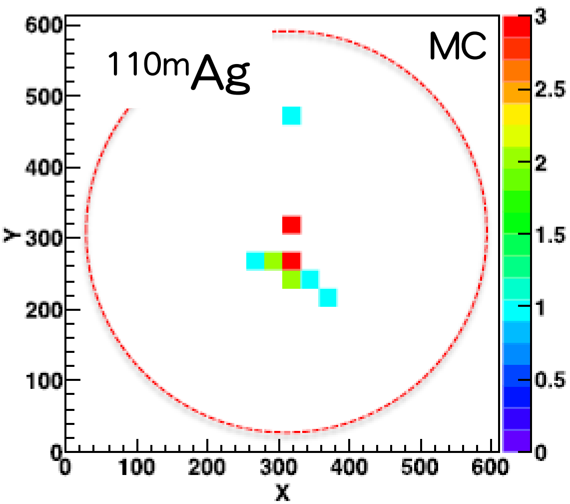
Angle of view: 20 deg
Resolution: ~5 cm

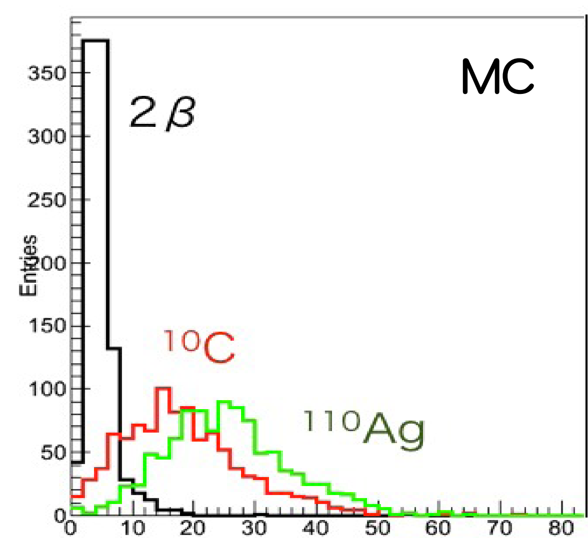


multi-anode PMTs
(or I.I. + CCD)

Reconstructed Image



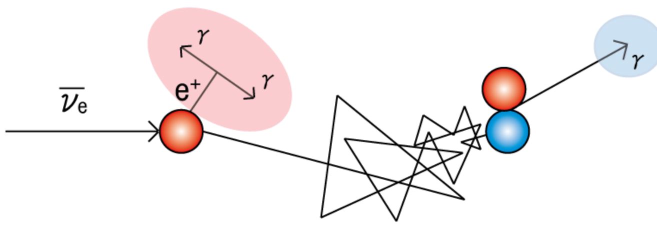




Directional Sensitivity (R&D)

Scintillation Imaging for Anti-Neutrino Events

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + p \rightarrow {}^2\mathrm{H} + \gamma$$

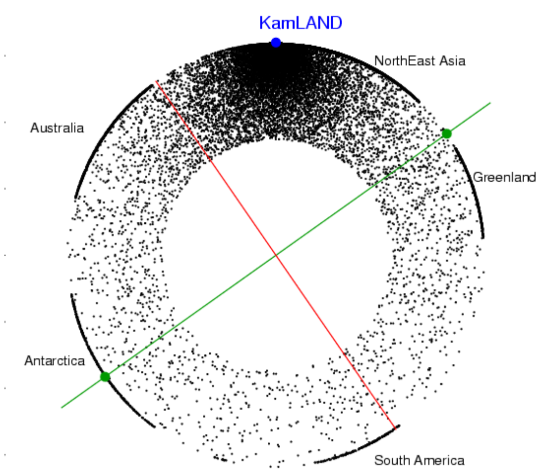


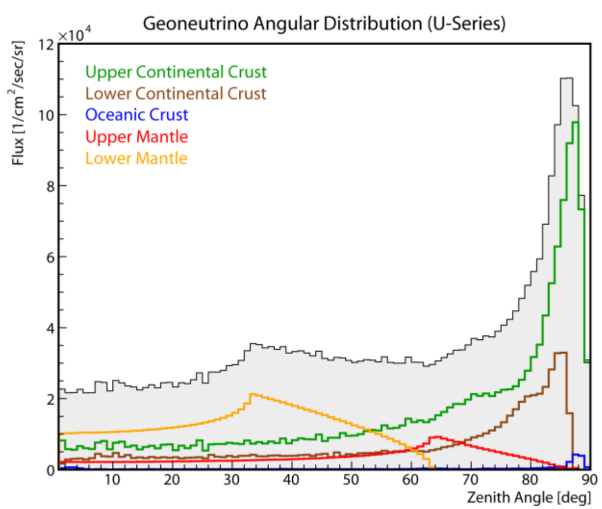
Neutrons remember neutrino direction
but forget it soon

For Directionality,
✓ Reduce neutron diffusion
✓ Eliminate gamma emission

Detecting Antineutrino Direction is a *Revolution* in Geophysics

3D Mapping of U & Th distributions in Earth interior
(with multi-site observation, or mobile detectors)





~50% Earth energy is from U/Th/K decay

U/Th are traces for Earth formation and evolution

Directional Sensitivity (R&D)

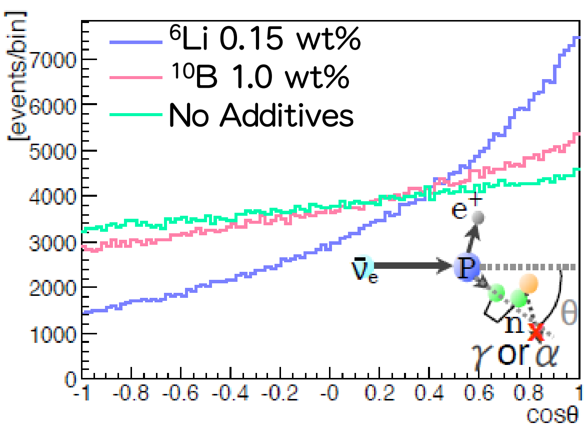
^{6}Li-loaded Liquid Scintillator

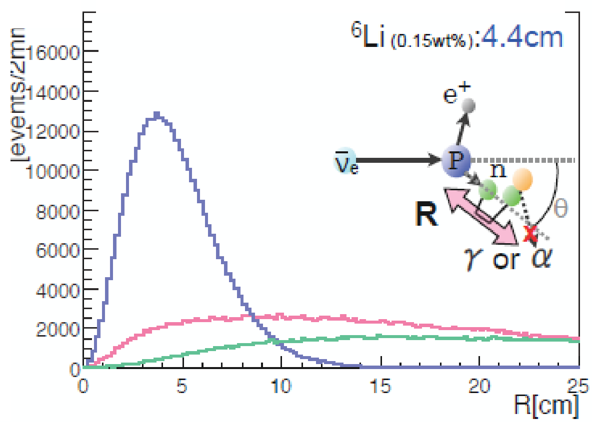
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

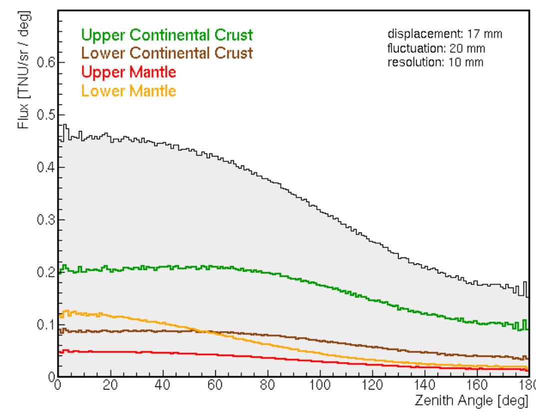
$$n + {}^6\mathrm{Li} \rightarrow {}^3\mathrm{H} + \alpha$$

- ✓ Large capture cross-section 940 barn (H: 0.3 barn)
- ✓ α-emission, no γ (Gd and ^{10}B both emit γ)

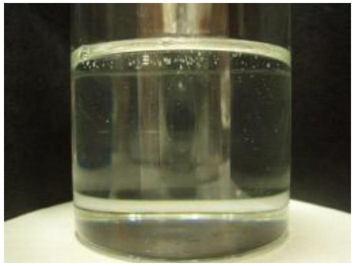
MC Simulation (0.15 wt% ^{6}Li)







Li-loaded Liquid Scintillator Development (Tohoku)



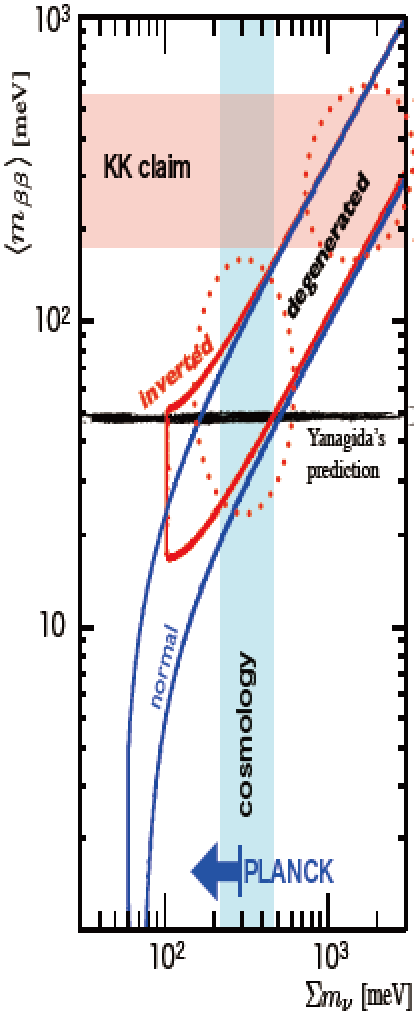
PC + PPC + POE + LiBr + H_2O (POE: surfactant)

0.8 wt% Li (^{6}Li abundance 7.59%, enrichment is possible)

Transparency 65cm@400nm, light yield 45% of KamLAND LS

Summary

KamLAND-Zen 0νββ



NME variation	← **published** ⟨160~330 meV
ongoing	← **running** ^{110m}Ag removed
2015~	Clean balloon
future	Improved E-res
dream	Zen at 30m deep

KamLAND Scintillation Detector Evolution

2002~

- Large Volume, Ultra-Pure
- Pile-up Free Readout (ATWD)

2010~

- Dead-time Free Readout for ^{10}C tagging etc

R&D

- Dead-space Free Container with scintillating balloon

R&D

- Scintillation Imaging for e/γ discrimination etc

R&D

- Directional Sensitivity for geoneutrinos, supernova, …

KamLAND Founders

VOLUME 90, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2003

First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance

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(KamLAND Collaboration)